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(54) **METHOD AND ASSEMBLY FOR FORMING COMPONENTS HAVING AN INTERNAL PASSAGE DEFINED THEREIN**

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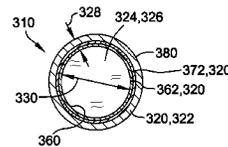
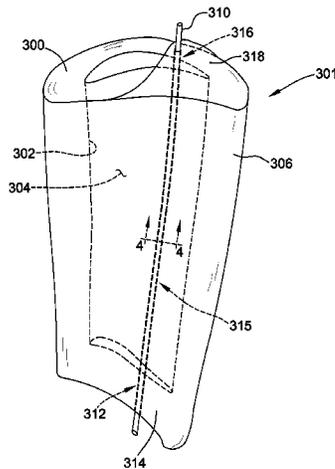
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(57) **ABSTRACT**
A method of forming a component having an internal passage defined therein includes positioning a jacketed core with respect to a mold. The jacketed core includes a hollow structure formed from at least a first material and a second material, and an inner core disposed within the hollow structure. The method also includes introducing a component material in a molten state into a cavity of the mold, and cooling the component material in the cavity to form the component. The inner core defines the internal passage within the component.

21 Claims, 11 Drawing Sheets



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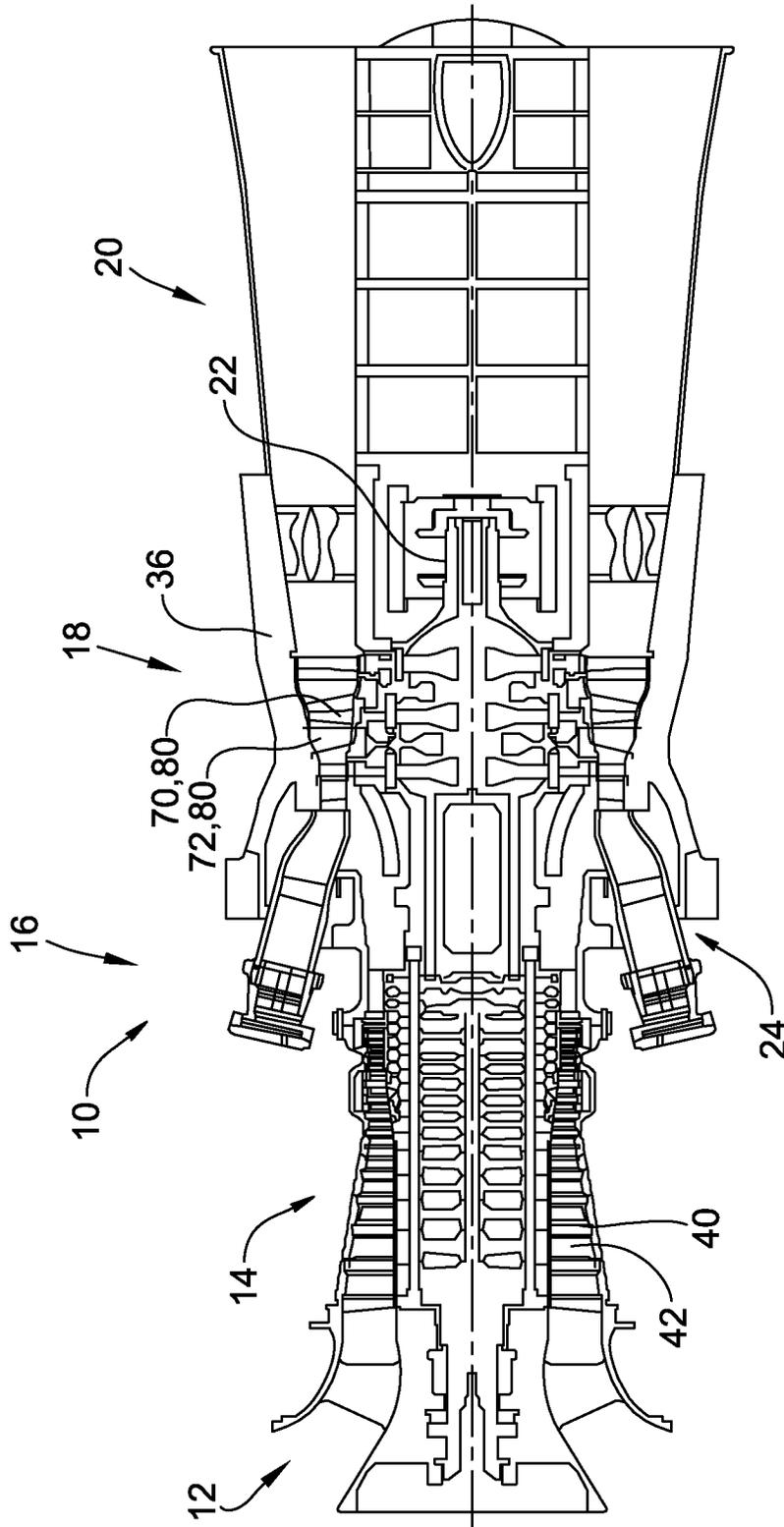


FIG. 1

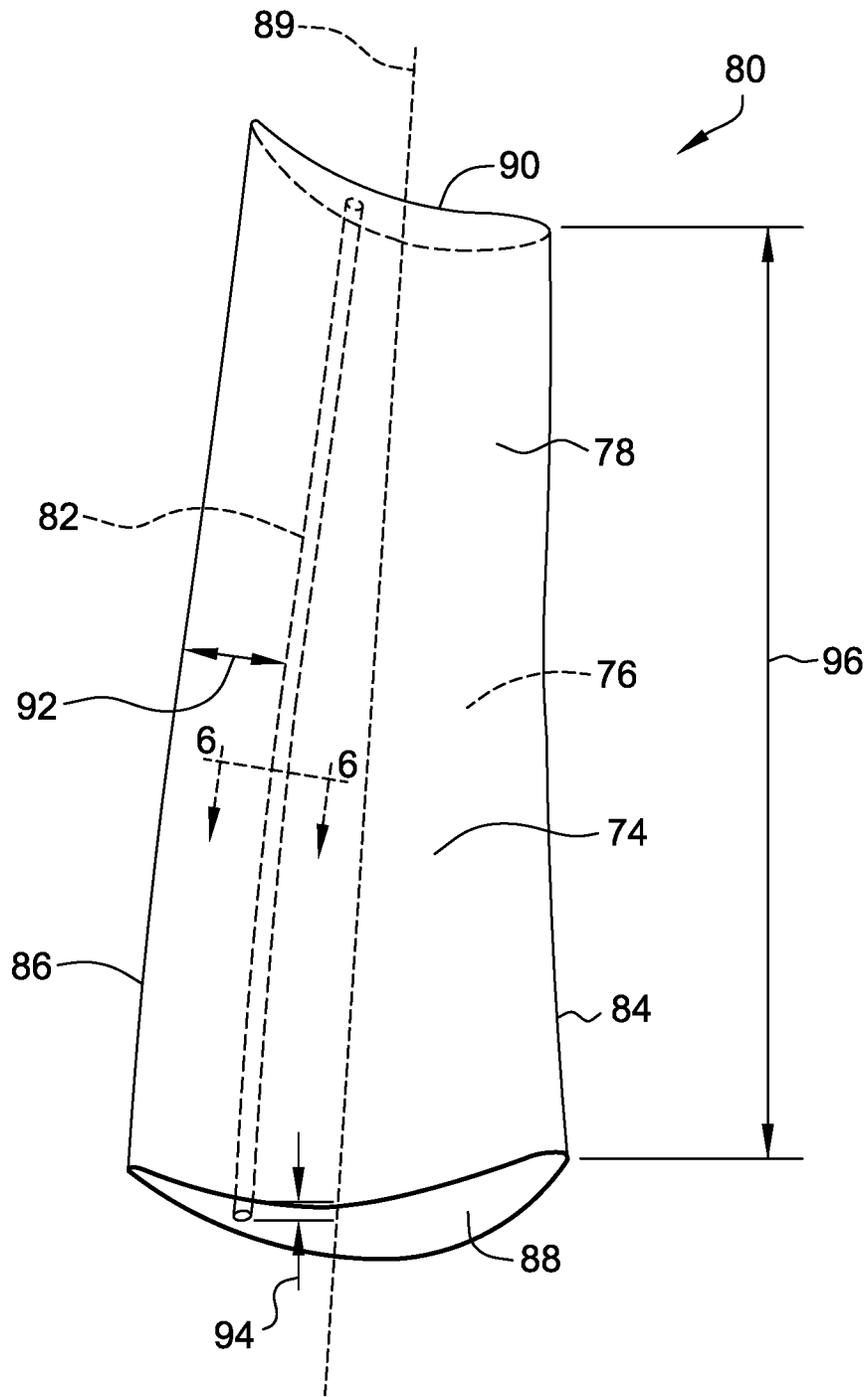


FIG. 2

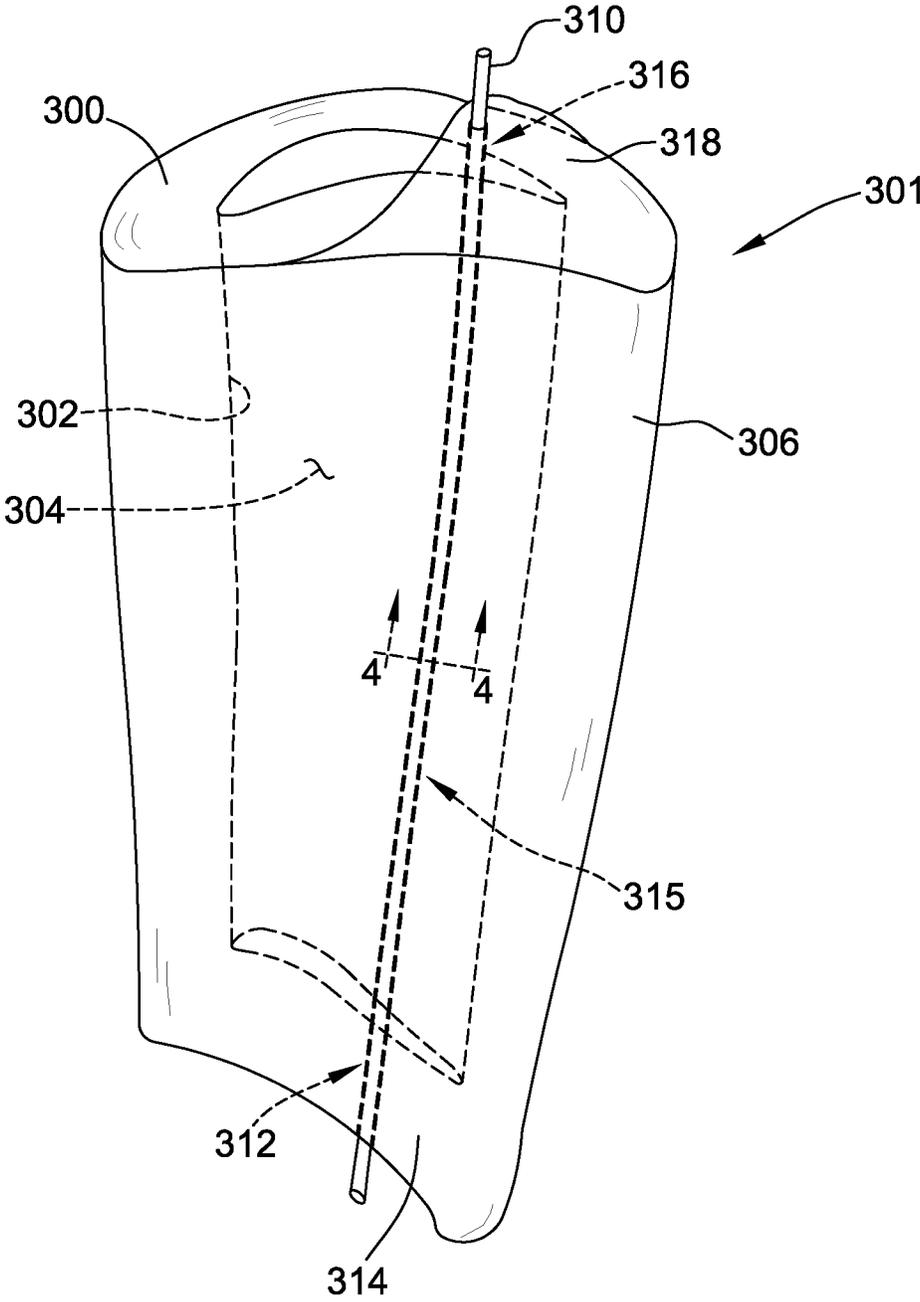


FIG. 3

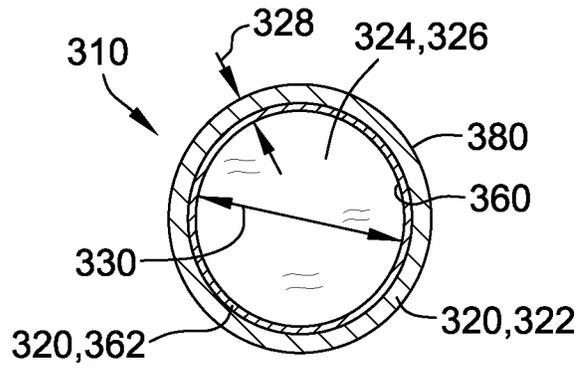


FIG. 4

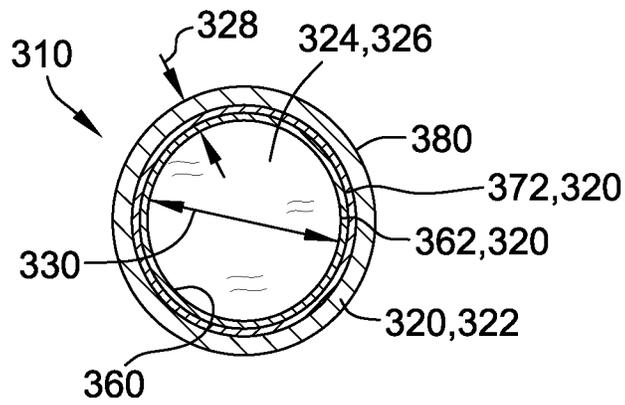


FIG. 5

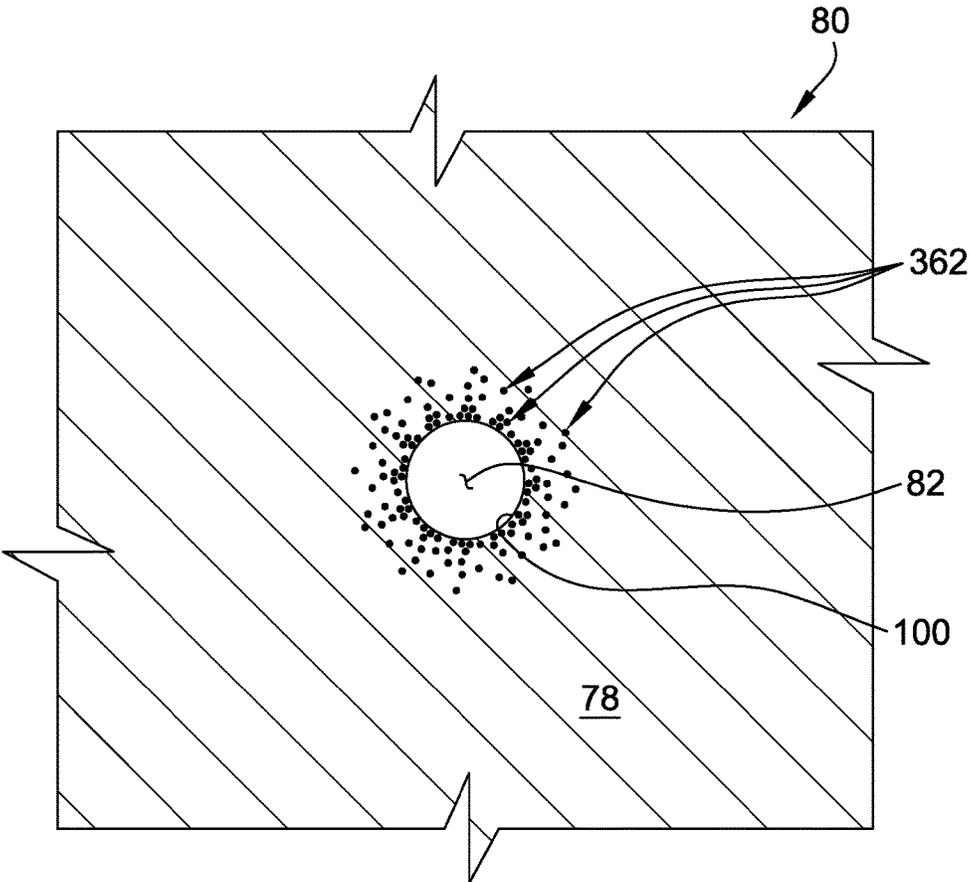


FIG. 6

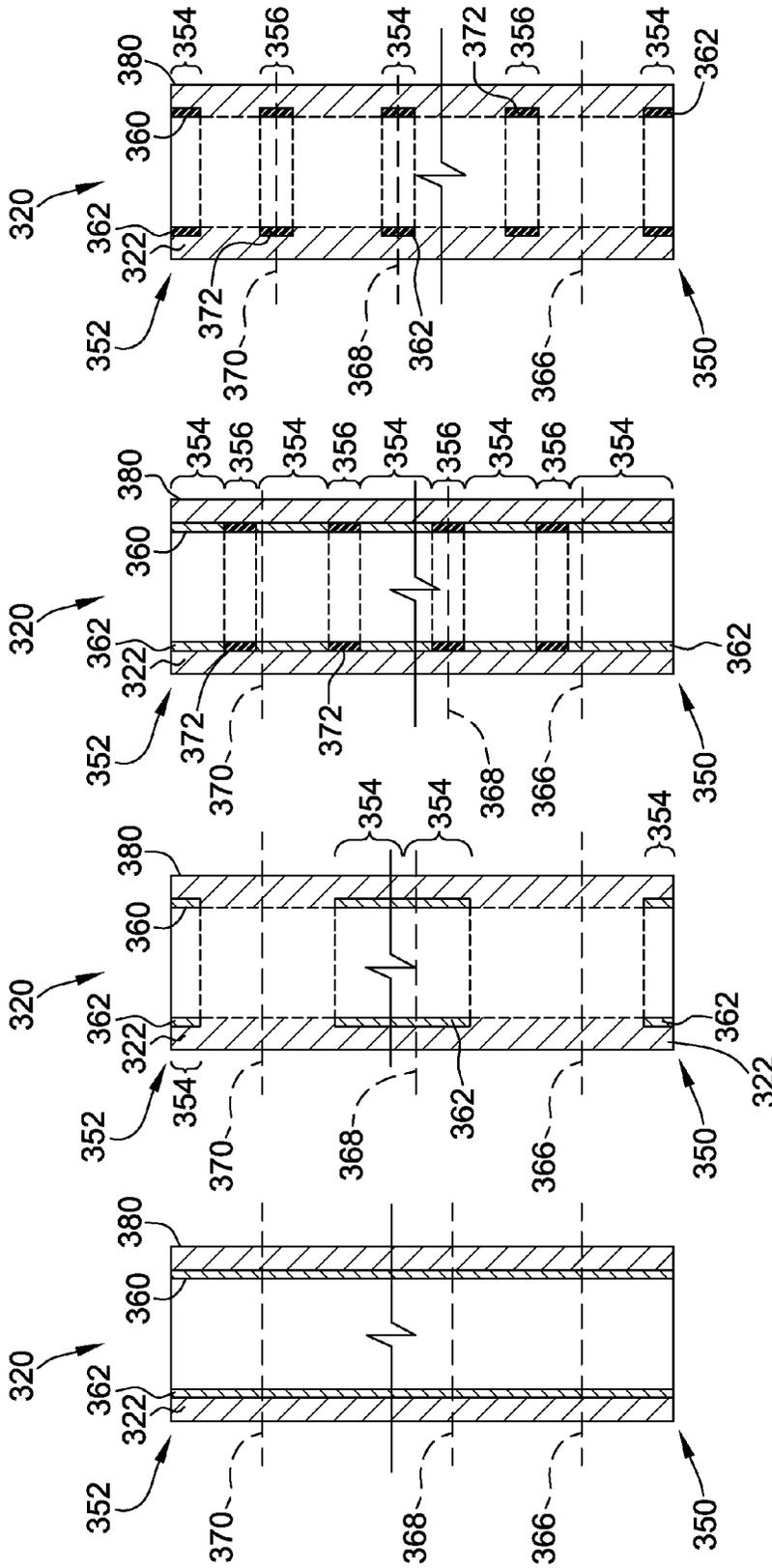


FIG. 7

FIG. 8

FIG. 9

FIG. 10

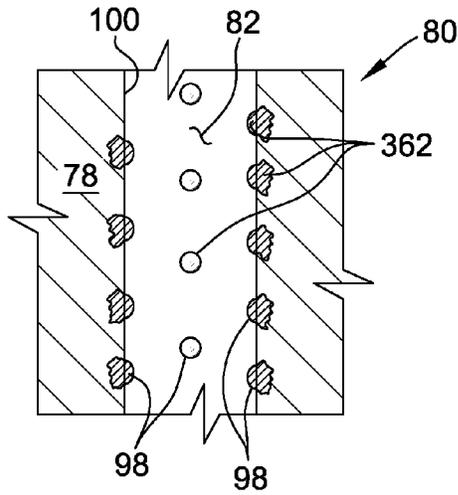


FIG. 11

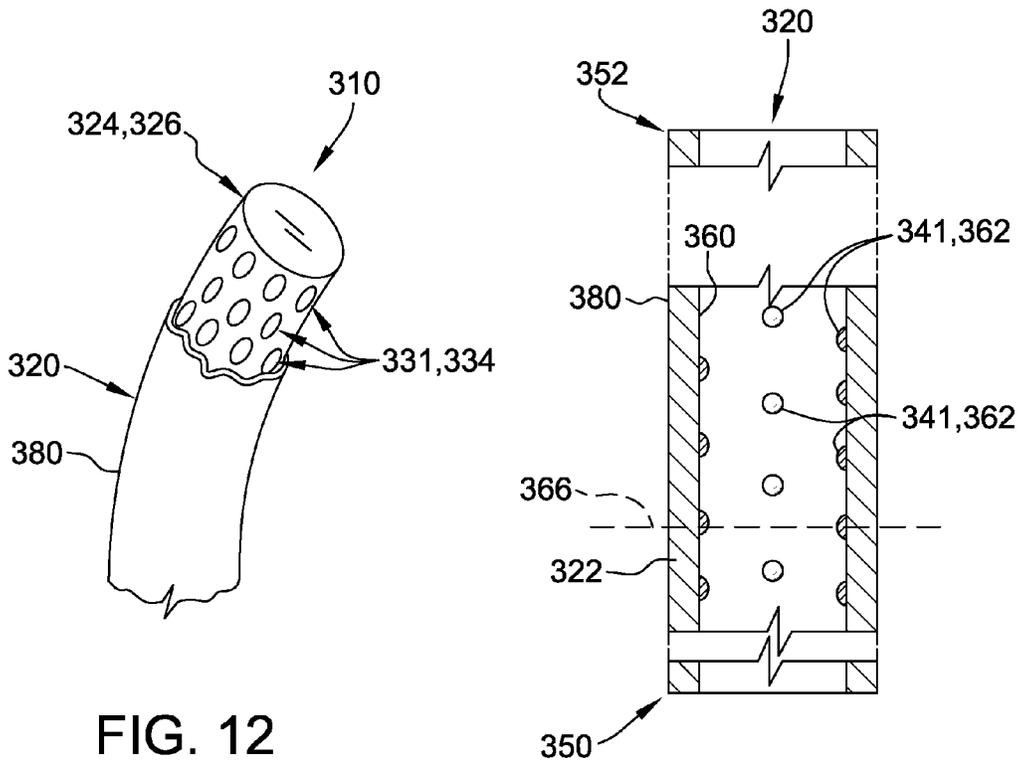


FIG. 12

FIG. 13

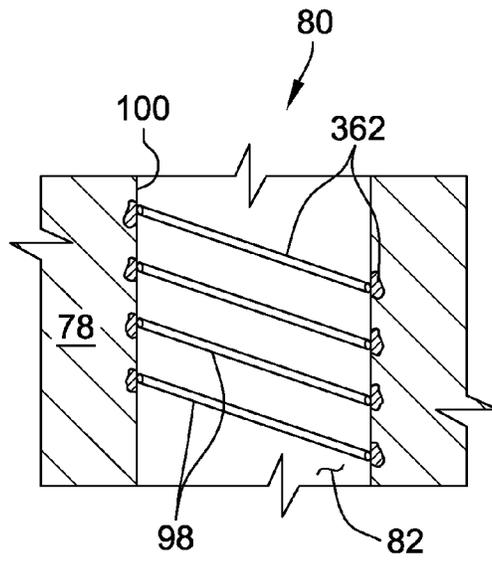


FIG. 14

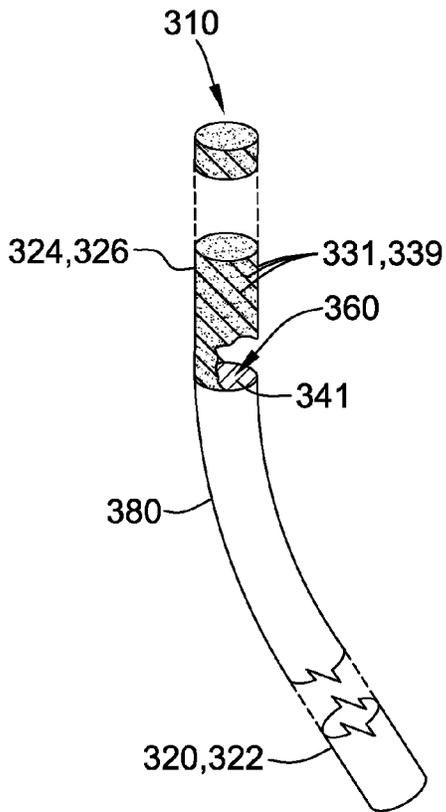


FIG. 15

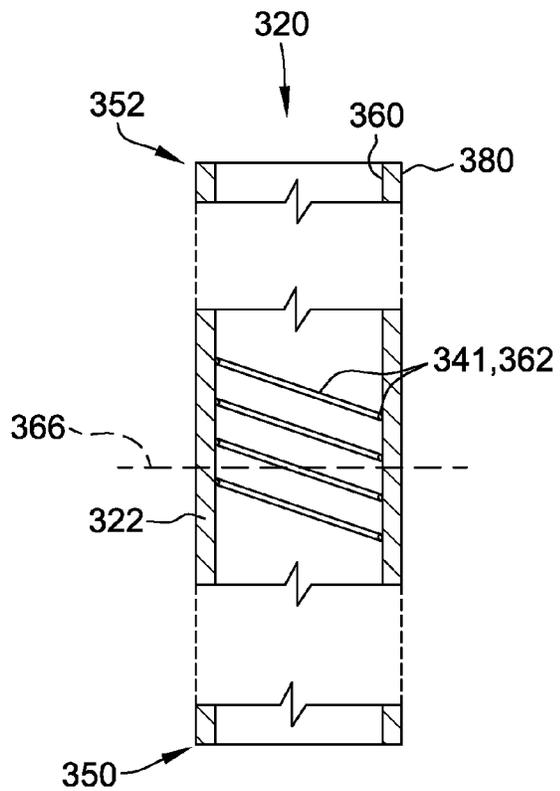


FIG. 16

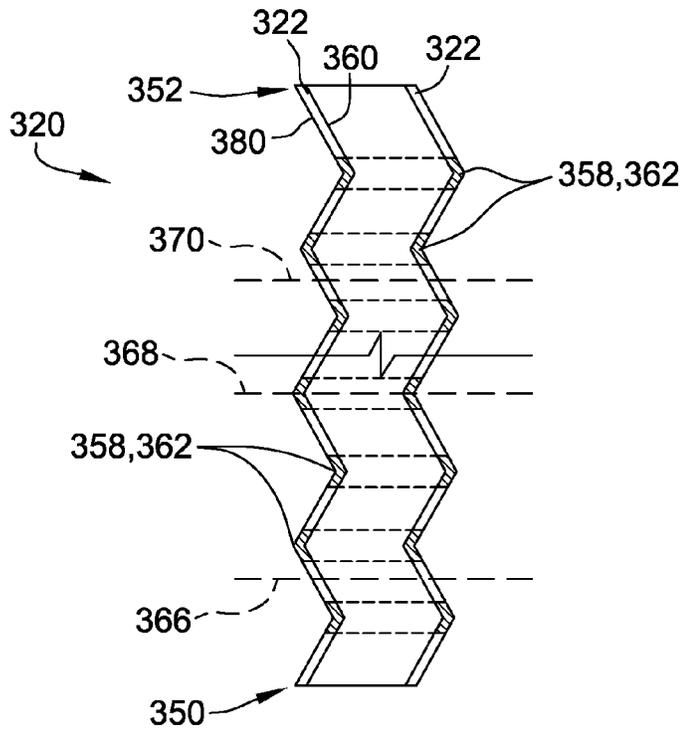


FIG. 17

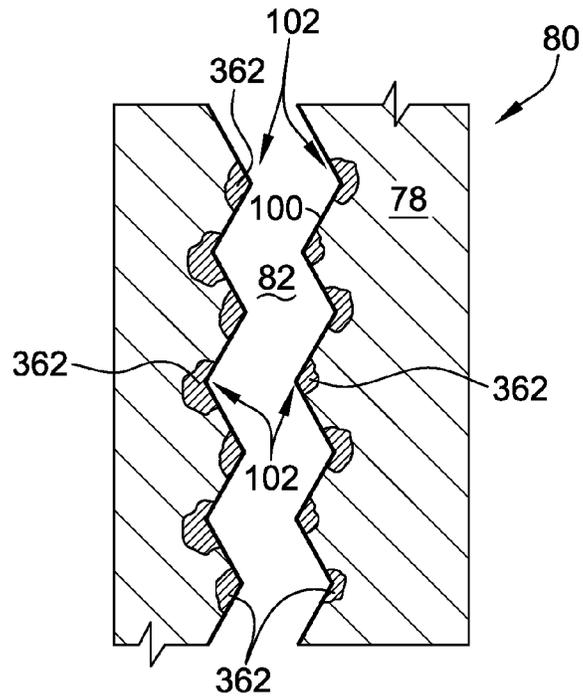


FIG. 18

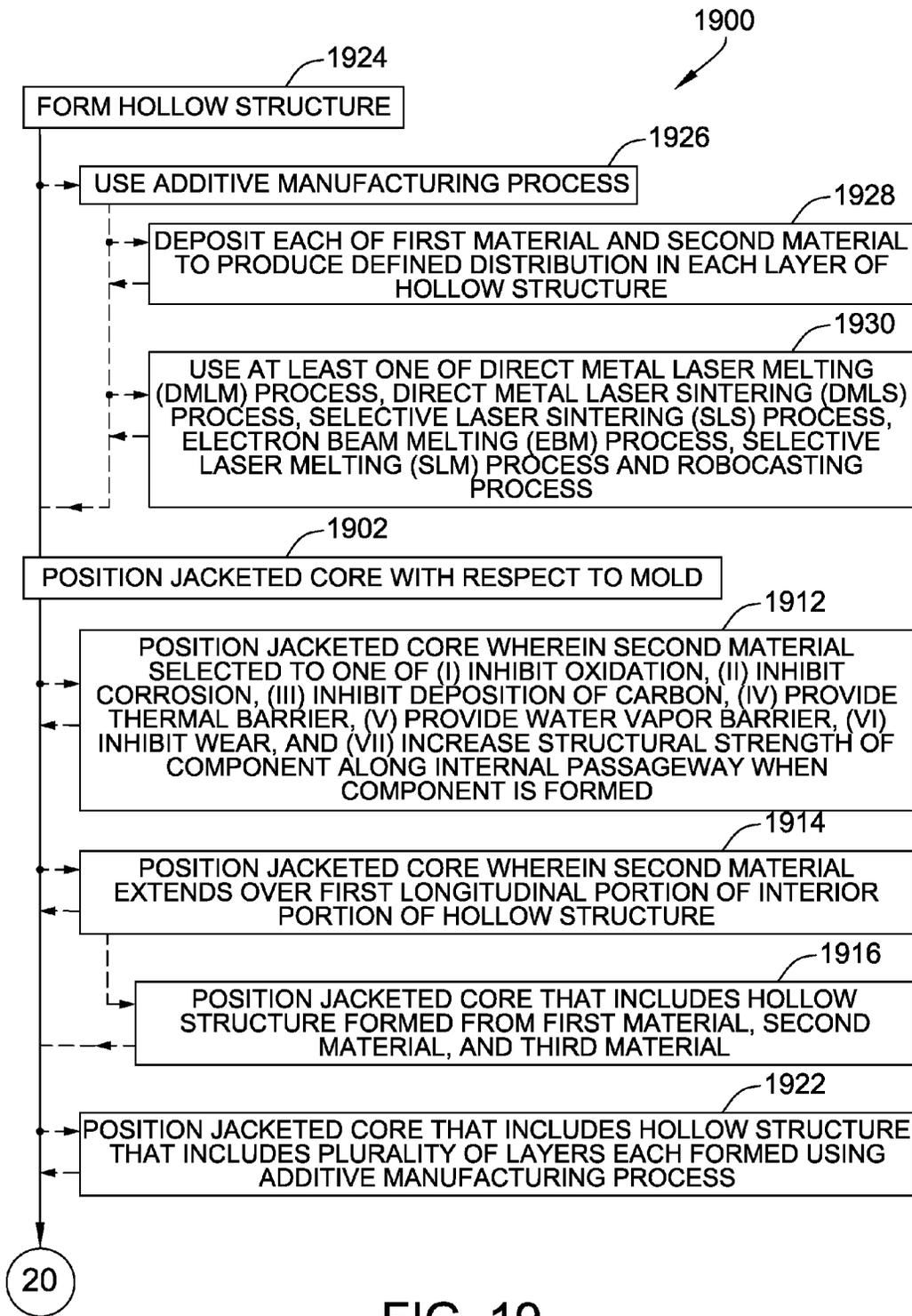


FIG. 19

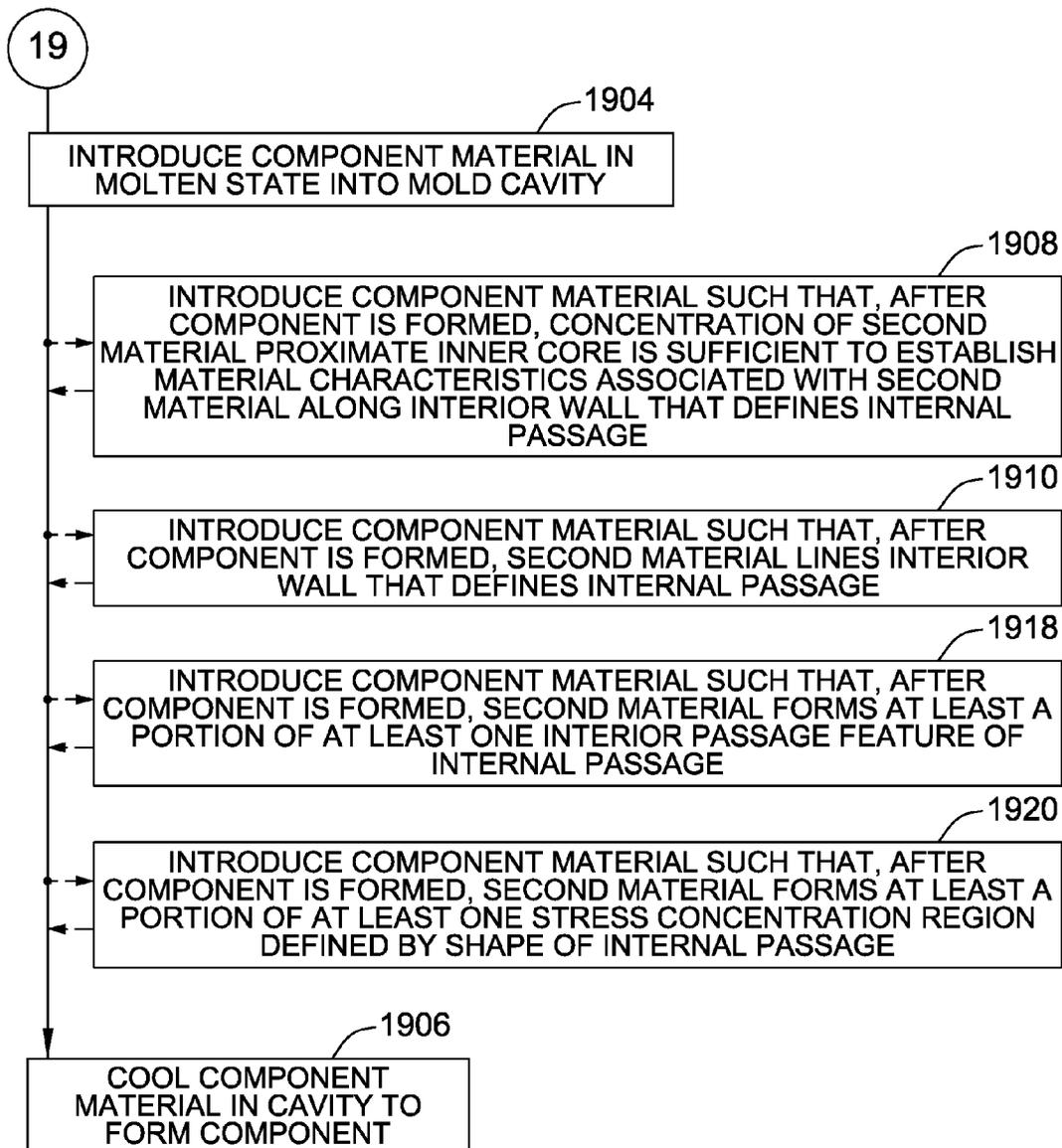


FIG. 20

METHOD AND ASSEMBLY FOR FORMING COMPONENTS HAVING AN INTERNAL PASSAGE DEFINED THEREIN

BACKGROUND

The field of the disclosure relates generally to components having an internal passage defined therein, and more particularly to forming interior walls that define the internal passages using a plurality of materials.

Some components require an internal passage to be defined therein, for example, in order to perform an intended function. For example, but not by way of limitation, some components, such as hot gas path components of gas turbines, are subjected to high temperatures. At least some such components have internal passages defined therein to receive a flow of a cooling fluid, such that the components are better able to withstand the high temperatures. For another example, but not by way of limitation, some components are subjected to friction at an interface with another component. At least some such components have internal passages defined therein to receive a flow of a lubricant to facilitate reducing the friction.

At least some known components having an internal passage defined therein are formed in a mold, with a core of ceramic material extending within the mold cavity at a location selected for the internal passage. After a molten metal alloy is introduced into the mold cavity around the ceramic core and cooled to form the component, the ceramic core is removed, such as by chemical leaching, to form the internal passage. Alternatively or additionally, at least some known components having an internal passage defined therein are initially formed without the internal passage, and the internal passage is formed in a subsequent process. For example, at least some known internal passages are formed by drilling the passage into the component, such as, but not limited to, using an electrochemical drilling process. In each case, the interior wall that defines the internal passage is defined by the metal alloy used to form the component. Thus, if the interior wall defines, for example, a stress concentration at a particular point, the metal alloy used to cast the entire component must be chosen to satisfy the relatively higher strength needs at that particular point, potentially increasing a cost of the component.

In addition, at least some known components having an internal passage defined therein exhibit improved performance of the intended function after a coating is applied to the interior wall. However, such coatings can be difficult or cost-prohibitive to apply completely and/or evenly to certain internal passageways, such as, but not limited to, internal passageways characterized by a high degree of nonlinearity, a complex cross-section, and/or a large length-to-diameter ratio.

BRIEF DESCRIPTION

In one aspect, a method of forming a component having an internal passage defined therein is provided. The method includes positioning a jacketed core with respect to a mold. The jacketed core includes a hollow structure formed from at least a first material and a second material, and an inner core disposed within the hollow structure. The method also includes introducing a component material in a molten state into a cavity of the mold, and cooling the component material in the cavity to form the component. The inner core defines the internal passage within the component.

In another aspect, a mold assembly for use in forming a component having an internal passage defined therein is provided. The mold assembly includes a mold defining a mold cavity therein, and a jacketed core positioned with respect to the mold. The jacketed core includes a hollow structure formed from at least a first material and a second material, and an inner core disposed within the hollow structure. The inner core is positioned to define the internal passage within the component when a component material in a molten state is introduced into the mold cavity and cooled to form the component.

DRAWINGS

FIG. 1 is a schematic diagram of an exemplary rotary machine;

FIG. 2 is a schematic perspective view of an exemplary component for use with the rotary machine shown in FIG. 1;

FIG. 3 is a schematic perspective view of an exemplary mold assembly for making the component shown in FIG. 2, the mold assembly including a jacketed core positioned with respect to a mold;

FIG. 4 is a schematic cross-section of an exemplary jacketed core for use with the mold assembly shown in FIG. 3, taken along lines 4-4 shown in FIG. 3;

FIG. 5 is a schematic cross-section of another exemplary jacketed core for use with the mold assembly shown in FIG. 3, taken along lines 4-4 shown in FIG. 3;

FIG. 6 is a cross-section of the component of FIG. 2, taken along lines 6-6 shown in FIG. 2;

FIG. 7 is a schematic sectional view of an exemplary embodiment of a hollow structure for use in forming the jacketed core shown in FIG. 3;

FIG. 8 is a schematic sectional view of another exemplary embodiment of a hollow structure for use in forming the jacketed core shown in FIG. 3;

FIG. 9 is a schematic sectional view of another exemplary embodiment of a hollow structure for use in forming the jacketed core shown in FIG. 3;

FIG. 10 is a schematic sectional view of another exemplary embodiment of a hollow structure for use in forming the jacketed core shown in FIG. 3;

FIG. 11 is a schematic sectional view of a portion of another exemplary component for use with the rotary machine shown in FIG. 1;

FIG. 12 is a schematic perspective cutaway view of another exemplary jacketed core for use with the mold assembly shown in FIG. 3 to form the component shown in FIG. 11;

FIG. 13 is a schematic sectional view of an exemplary embodiment of a hollow structure for use in forming the jacketed core shown in FIG. 12;

FIG. 14 is a schematic sectional view of a portion of another exemplary component for use with the rotary machine shown in FIG. 1;

FIG. 15 is a schematic perspective cutaway view of another exemplary jacketed core for use with the mold assembly shown in FIG. 3 to form the component shown in FIG. 14;

FIG. 16 is a schematic sectional view of an exemplary embodiment of a hollow structure for use in forming the jacketed core shown in FIG. 15;

FIG. 17 is a schematic sectional view of a portion of another exemplary component for use with the rotary machine shown in FIG. 1;

FIG. 18 is a schematic sectional view of an exemplary embodiment of a hollow structure for use in forming a

jacketed core for use with the mold assembly shown in FIG. 3 to form the component shown in FIG. 17;

FIG. 19 is a flow diagram of an exemplary method of forming a component having an internal passage defined therein, such as a component for use with the rotary machine shown in FIG. 1; and

FIG. 20 is a continuation of the flow diagram from FIG. 19.

DETAILED DESCRIPTION

In the following specification and the claims, reference will be made to a number of terms, which shall be defined to have the following meanings.

The singular forms “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

“Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms such as “about,” “approximately,” and “substantially” is not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be identified. Such ranges may be combined and/or interchanged, and include all the sub-ranges contained therein unless context or language indicates otherwise.

The exemplary components and methods described herein overcome at least some of the disadvantages associated with known assemblies and methods for forming a component having an internal passage defined therein, with a material other than the component material positioned proximate the internal passage. The embodiments described herein provide a jacketed core positioned with respect to a mold. The jacketed core includes a hollow structure and an inner core disposed within the hollow structure. The inner core extends within the mold cavity to define a position of the internal passage within the component to be formed in the mold. The hollow structure is formed from a first material and a second material. The second material is strategically distributed within the hollow structure, such as by an additive manufacturing process, such that the second material is selectively positioned along the internal passage when the component is formed in the mold.

FIG. 1 is a schematic view of an exemplary rotary machine 10 having components for which embodiments of the current disclosure may be used. In the exemplary embodiment, rotary machine 10 is a gas turbine that includes an intake section 12, a compressor section 14 coupled downstream from intake section 12, a combustor section 16 coupled downstream from compressor section 14, a turbine section 18 coupled downstream from combustor section 16, and an exhaust section 20 coupled downstream from turbine section 18. A generally tubular casing 36 at least partially encloses one or more of intake section 12, compressor section 14, combustor section 16, turbine section 18, and exhaust section 20. In alternative embodiments, rotary machine 10 is any rotary machine for which components formed with internal passages as described herein are suitable. Moreover, although embodiments of the present dis-

closure are described in the context of a rotary machine for purposes of illustration, it should be understood that the embodiments described herein are applicable in any context that involves a component suitably formed with an internal passage defined therein.

In the exemplary embodiment, turbine section 18 is coupled to compressor section 14 via a rotor shaft 22. It should be noted that, as used herein, the term “couple” is not limited to a direct mechanical, electrical, and/or communication connection between components, but may also include an indirect mechanical, electrical, and/or communication connection between multiple components.

During operation of gas turbine 10, intake section 12 channels air towards compressor section 14. Compressor section 14 compresses the air to a higher pressure and temperature. More specifically, rotor shaft 22 imparts rotational energy to at least one circumferential row of compressor blades 40 coupled to rotor shaft 22 within compressor section 14. In the exemplary embodiment, each row of compressor blades 40 is preceded by a circumferential row of compressor stator vanes 42 extending radially inward from casing 36 that direct the air flow into compressor blades 40. The rotational energy of compressor blades 40 increases a pressure and temperature of the air. Compressor section 14 discharges the compressed air towards combustor section 16.

In combustor section 16, the compressed air is mixed with fuel and ignited to generate combustion gases that are channeled towards turbine section 18. More specifically, combustor section 16 includes at least one combustor 24, in which a fuel, for example, natural gas and/or fuel oil, is injected into the air flow, and the fuel-air mixture is ignited to generate high temperature combustion gases that are channeled towards turbine section 18.

Turbine section 18 converts the thermal energy from the combustion gas stream to mechanical rotational energy. More specifically, the combustion gases impart rotational energy to at least one circumferential row of rotor blades 70 coupled to rotor shaft 22 within turbine section 18. In the exemplary embodiment, each row of rotor blades 70 is preceded by a circumferential row of turbine stator vanes 72 extending radially inward from casing 36 that direct the combustion gases into rotor blades 70. Rotor shaft 22 may be coupled to a load (not shown) such as, but not limited to, an electrical generator and/or a mechanical drive application. The exhausted combustion gases flow downstream from turbine section 18 into exhaust section 20. Components of rotary machine 10 are designated as components 80. Components 80 proximate a path of the combustion gases are subjected to high temperatures during operation of rotary machine 10. Additionally or alternatively, components 80 include any component suitably formed with an internal passage defined therein.

FIG. 2 is a schematic perspective view of an exemplary component 80, illustrated for use with rotary machine 10 (shown in FIG. 1). Component 80 includes at least one internal passage 82 defined therein by an interior wall 100. For example, a cooling fluid is provided to internal passage 82 during operation of rotary machine 10 to facilitate maintaining component 80 below a temperature of the hot combustion gases. Although only one internal passage 82 is illustrated, it should be understood that component 80 includes any suitable number of internal passages 82 formed as described herein.

Component 80 is formed from a component material 78. In the exemplary embodiment, component material 78 is a suitable nickel-based superalloy. In alternative embodi-

ments, component material **78** is at least one of a cobalt-based superalloy, an iron-based alloy, and a titanium-based alloy. In other alternative embodiments, component material **78** is any suitable material that enables component **80** to be formed as described herein.

In the exemplary embodiment, component **80** is one of rotor blades **70** or stator vanes **72**. In alternative embodiments, component **80** is another suitable component of rotary machine **10** that is capable of being formed with an internal passage as described herein. In still other embodiments, component **80** is any component for any suitable application that is suitably formed with an internal passage defined therein.

In the exemplary embodiment, rotor blade **70**, or alternatively stator vane **72**, includes a pressure side **74** and an opposite suction side **76**. Each of pressure side **74** and suction side **76** extends from a leading edge **84** to an opposite trailing edge **86**. In addition, rotor blade **70**, or alternatively stator vane **72**, extends from a root end **88** to an opposite tip end **90**, defining a blade length **96**. In alternative embodiments, rotor blade **70**, or alternatively stator vane **72**, has any suitable configuration that is capable of being formed with an internal passage as described herein.

In certain embodiments, blade length **96** is at least about 25.4 centimeters (cm) (10 inches). Moreover, in some embodiments, blade length **96** is at least about 50.8 cm (20 inches). In particular embodiments, blade length **96** is in a range from about 61 cm (24 inches) to about 101.6 cm (40 inches). In alternative embodiments, blade length **96** is less than about 25.4 cm (10 inches). For example, in some embodiments, blade length **96** is in a range from about 2.54 cm (1 inch) to about 25.4 cm (10 inches). In other alternative embodiments, blade length **96** is greater than about 101.6 cm (40 inches).

In the exemplary embodiment, internal passage **82** extends from root end **88** to tip end **90**. In alternative embodiments, internal passage **82** extends within component **80** in any suitable fashion, and to any suitable extent, that enables internal passage **82** to be formed as described herein. In certain embodiments, internal passage **82** is nonlinear. For example, component **80** is formed with a predefined twist along an axis **89** defined between root end **88** and tip end **90**, and internal passage **82** has a curved shape complementary to the axial twist. In some embodiments, internal passage **82** is positioned at a substantially constant distance **94** from pressure side **74** along a length of internal passage **82**. Alternatively or additionally, a chord of component **80** tapers between root end **88** and tip end **90**, and internal passage **82** extends nonlinearly complementary to the taper, such that internal passage **82** is positioned at a substantially constant distance **92** from trailing edge **86** along the length of internal passage **82**. In alternative embodiments, internal passage **82** has a nonlinear shape that is complementary to any suitable contour of component **80**. In other alternative embodiments, internal passage **82** is nonlinear and other than complementary to a contour of component **80**. In some embodiments, internal passage **82** having a nonlinear shape facilitates satisfying a preselected cooling criterion for component **80**. In alternative embodiments, internal passage **82** extends linearly.

In some embodiments, internal passage **82** has a substantially circular cross-sectional perimeter. In alternative embodiments, internal passage **82** has a substantially ovoid cross-sectional perimeter. In other alternative embodiments, internal passage **82** has any suitably shaped cross-sectional perimeter that enables internal passage **82** to be formed as described herein. Moreover, in certain embodiments, a shape

of the cross-sectional perimeter of internal passage **82** is substantially constant along a length of internal passage **82**. In alternative embodiments, the shape of the cross-sectional perimeter of internal passage **82** varies along a length of internal passage **82** in any suitable fashion that enables internal passage **82** to be formed as described herein.

FIG. 3 is a schematic perspective view of a mold assembly **301** for making component **80** (shown in FIG. 2). Mold assembly **301** includes a jacketed core **310** positioned with respect to a mold **300**. FIG. 4 is a schematic cross-section of an embodiment of jacketed core **310** taken along lines 4-4 shown in FIG. 3. With reference to FIGS. 2-4, an interior wall **302** of mold **300** defines a mold cavity **304**. Interior wall **302** defines a shape corresponding to an exterior shape of component **80**, such that component material **78** in a molten state can be introduced into mold cavity **304** and cooled to form component **80**. It should be recalled that, although component **80** in the exemplary embodiment is rotor blade **70**, or alternatively stator vane **72**, in alternative embodiments component **80** is any component suitably formable with an internal passage defined therein, as described herein.

Jacketed core **310** is positioned with respect to mold **300** such that a portion **315** of jacketed core **310** extends within mold cavity **304**. Jacketed core **310** includes a hollow structure **320** formed from a first material **322** and a second material **362**. Jacketed core **310** also includes an inner core **324** disposed within hollow structure **320** and formed from an inner core material **326**. Inner core **324** is shaped to define a shape of internal passage **82**, and inner core **324** of portion **315** of jacketed core **310** positioned within mold cavity **304** defines internal passage **82** within component **80** when component **80** is formed.

Hollow structure **320** includes an outer wall **380** that substantially encloses inner core **324** along a length of inner core **324**. An interior portion **360** of hollow structure **320** is located interiorly with respect to outer wall **380**, such that inner core **324** is complementarily shaped by interior portion **360** of hollow structure **320**. In certain embodiments, hollow structure **320** defines a generally tubular shape. For example, but not by way of limitation, hollow structure **320** is initially formed from a substantially straight metal tube that is suitably manipulated into a nonlinear shape, such as a curved or angled shape, as necessary to define a selected nonlinear shape of inner core **324** and, thus, of internal passage **82**. In alternative embodiments, hollow structure **320** defines any suitable shape that enables inner core **324** to define a shape of internal passage **82** as described herein.

In the exemplary embodiment, hollow structure **320** has a wall thickness **328** that is less than a characteristic width **330** of inner core **324**. Characteristic width **330** is defined herein as the diameter of a circle having the same cross-sectional area as inner core **324**. In alternative embodiments, hollow structure **320** has a wall thickness **328** that is other than less than characteristic width **330**. A shape of a cross-section of inner core **324** is circular in the exemplary embodiment shown in FIGS. 3-5. Alternatively, the shape of the cross-section of inner core **324** corresponds to any suitable shape of the cross-section of internal passage **82** that enables internal passage **82** to function as described herein.

In certain embodiments, first material **322** is selected to provide structural support to jacketed core **310**. In the exemplary embodiment, hollow core **320** includes second material **362** disposed adjacent at least a portion of inner core **324**, and first material **322** disposed adjacent outer wall **380**. More specifically, second material **362** defines interior portion **360** of hollow structure **320**, and first material **322**

defines outer wall **380** of hollow structure **320**. In alternative embodiments, first material **322** and second material **362** are disposed in any suitable arrangement within hollow structure **320** that enables hollow structure **320** to function as described herein.

In some embodiments, second material **362** is selected to enhance a performance of internal passage **82** after component **80** is formed, as will be described herein. For example, but not by way of limitation, second material **362** is selected to inhibit oxidation of component material **78** along interior wall **100**. Additionally or alternatively, but not by way of limitation, second material **362** is selected to inhibit corrosion of component material **78** along interior wall **100**. Additionally or alternatively, but not by way of limitation, second material **362** is selected to inhibit deposition of carbon on component material **78** along interior wall **100**. Additionally or alternatively, but not by way of limitation, second material **362** is selected to provide a thermal barrier for component material **78** along interior wall **100**. Additionally or alternatively, but not by way of limitation, first coating material **366** is selected to provide a water vapor barrier for component material **78** along interior wall **100**. Additionally or alternatively, but not by way of limitation, second material **362** is selected to inhibit wear, such as but not limited to erosion, of component material **78** along interior wall **100**. Additionally or alternatively, second material **362** is selected to be any suitable material that provides or facilitates any other selected characteristic of internal passage **82** when disposed along interior wall **100**. In addition, although second material **362** is referred to as a single material, it should be understood that, in some embodiments, second material **362** includes a mixture of a plurality of performance-enhancing constituents.

In certain embodiments, hollow structure **320** is formed from any suitable number of materials in addition to first material **322** and second material **362**. For example, FIG. **5** is a schematic cross-section of another embodiment of jacketed core **310** taken along lines **4-4** shown in FIG. **3**. In the exemplary embodiment, jacketed core **310** includes second material **362** disposed adjacent at least a portion of inner core **324**, first material **322** disposed adjacent outer wall **380**, and at least a third material **372** disposed radially between second material **362** and first material **322**. In some embodiments, second material **362** again is selected from at least one of (i) an oxidation-inhibiting material, (ii) a corrosion-inhibiting material, (iii) a carbon-deposition-inhibiting material, (iv) a thermal barrier material, (v) a water vapor barrier material, and (vi) a wear-inhibiting material, and third material **372** is selected from another of (i) an oxidation-inhibiting material, (ii) a corrosion-inhibiting material, (iii) a carbon-deposition-inhibiting material, (iv) a thermal barrier material, (v) a water vapor barrier material, and (vi) a wear-inhibiting material. In alternative embodiments, third material **372** is a bond coat material that facilitates bonding of second material **362** to at least one of first material **322** and component material **78**. In other alternative embodiments, third material **372** is any suitable material that enables jacketed core **310** to function as described herein.

With reference to FIGS. **2-5**, mold **300** is formed from a mold material **306**. In the exemplary embodiment, mold material **306** is a refractory ceramic material selected to withstand a high temperature environment associated with the molten state of component material **78** used to form component **80**. In alternative embodiments, mold material **306** is any suitable material that enables component **80** to be formed as described herein. Moreover, in the exemplary

embodiment, mold **300** is formed by a suitable investment casting process. For example, but not by way of limitation, a suitable pattern material, such as wax, is injected into a suitable pattern die to form a pattern (not shown) of component **80**, the pattern is repeatedly dipped into a slurry of mold material **306** which is allowed to harden to create a shell of mold material **306**, and the shell is dewaxed and fired to form mold **300**. In alternative embodiments, mold **300** is formed by any suitable method that enables mold **300** to function as described herein.

In certain embodiments, jacketed core **310** is secured relative to mold **300** such that jacketed core **310** remains fixed relative to mold **300** during a process of forming component **80**. For example, jacketed core **310** is secured such that a position of jacketed core **310** does not shift during introduction of molten component material **78** into mold cavity **304** surrounding jacketed core **310**. In some embodiments, jacketed core **310** is coupled directly to mold **300**. For example, in the exemplary embodiment, a tip portion **312** of jacketed core **310** is rigidly encased in a tip portion **314** of mold **300**. Additionally or alternatively, a root portion **316** of jacketed core **310** is rigidly encased in a root portion **318** of mold **300** opposite tip portion **314**. For example, but not by way of limitation, mold **300** is formed by investment casting as described above, and jacketed core **310** is securely coupled to the suitable pattern die such that tip portion **312** and root portion **316** extend out of the pattern die, while portion **315** extends within a cavity of the die. The pattern material is injected into the die around jacketed core **310** such that portion **315** extends within the pattern. The investment casting causes mold **300** to encase tip portion **312** and/or root portion **316**. Additionally or alternatively, jacketed core **310** is secured relative to mold **300** in any other suitable fashion that enables the position of jacketed core **310** relative to mold **300** to remain fixed during a process of forming component **80**.

First material **322** is selected to be at least partially absorbable by molten component material **78**. In certain embodiments, component material **78** is an alloy, and first material **322** is at least one constituent material of the alloy. For example, in the exemplary embodiment, component material **78** is a nickel-based superalloy, and first material **322** is substantially nickel, such that first material **322** is substantially absorbable by component material **78** when component material **78** in the molten state is introduced into mold cavity **304**. In alternative embodiments, component material **78** is any suitable alloy, and first material **322** is at least one material that is at least partially absorbable by the molten alloy. For example, component material **78** is a cobalt-based superalloy, and first material **322** is substantially cobalt. For another example, component material **78** is an iron-based alloy, and first material **322** is substantially iron. For another example, component material **78** is a titanium-based alloy, and first material **322** is substantially titanium.

In certain embodiments, second material **362** also is selected to be at least partially absorbable by molten component material **78**, as described above with respect to first material **322**. For example, component material **78** is a first alloy of a base metal, and second material **362** is a second alloy of the same base metal. In some such embodiments, second material **362** is selected to have an improved physical characteristic, such as, but not limited to, an improved structural strength characteristic, as compared to component material **78**. Moreover, in some embodiments in which hollow structure **320** includes materials in addition to first material **322** and second material **362**, the additional mate-

rials, such as, but not limited to, third material 372, also are selected to be at least partially absorbable by molten component material 78, as described above with respect to first material 322 and second material 362.

In certain embodiments, wall thickness 328 is sufficiently thin such that first material 322 and second material 362 of portion 315 of jacketed core 310, that is, the portion that extends within mold cavity 304, are substantially absorbed by component material 78 when component material 78 in the molten state is introduced into mold cavity 304. For example, in some such embodiments, first material 322 and second material 362 are substantially absorbed by component material 78 such that no discrete boundary delineates hollow structure 320 from component material 78 after component material 78 is cooled. Moreover, in some such embodiments, first material 322 and second material 362 are substantially absorbed such that, after component material 78 is cooled, first material 322 and second material 362 are substantially uniformly distributed within component material 78. For example, each of a concentration of first material 322 and a concentration of second material 362 proximate inner core 324 is not detectably higher than a concentration of first material 322 and a concentration of second material 362 at other locations within component 80.

In alternative embodiments, wall thickness 328 is selected such that at least one of first material 322 and second material 362 are other than substantially absorbed by component material 78. For example, in some embodiments, after component material 78 is cooled, at least one of first material 322 and second material 362 is other than substantially uniformly distributed within component material 78. For example, at least one of a concentration of first material 322 proximate inner core 324 and a concentration of second material 362 is detectably higher than a respective concentration of first material 322 or second material 362 at other locations within component 80. In some such embodiments, at least one of first material 322 and second material 362 are partially absorbed by component material 78 such that a discrete boundary delineates hollow structure 320 from component material 78 after component material 78 is cooled. Moreover, in some such embodiments, at least one of first material 322 and second material 362 are partially absorbed by component material 78 such that at least a portion of hollow structure 320 proximate inner core 324 remains intact after component material 78 is cooled.

In some such embodiments, after component 80 is formed, a concentration of second material 362 proximate inner core 324 is detectably higher than a concentration of second material 362 at other locations within component 80. Thus, after inner core 324 is removed from component 80 to form internal passage 82, the concentration of second material 362 proximate interior wall 100 is detectably higher than the concentration of second material 362 at other locations within component 80. Moreover, in some such embodiments, second material 362 lines at least a portion of interior wall 100 that defines internal passage 82.

For example, FIG. 6 is a cross-section of component 80 taken along lines 6-6 shown in FIG. 2, and schematically illustrates a gradient distribution of second material 362 proximate interior wall 100. A distribution of first material 322 within component 80 is omitted from FIG. 6 for clarity. In some embodiments, a concentration of second material 362 proximate interior wall 100 is sufficient to establish at least one material characteristic associated with second material 362 along at least a portion of interior wall 100. Moreover, in some embodiments, a concentration of second material 362 proximate interior wall 100 is sufficient such

that at least a portion of second material 362 lines at least a portion of interior wall 100 that defines internal passage 82.

Moreover, in certain embodiments in which hollow structure 320 includes materials in addition to first material 322 and second material 362, the additional materials, such as, but not limited to, third material 372, are distributed proximate interior wall 100 in similar fashion after component 80 is formed. For example, a concentration of third material 372 proximate interior wall 100 is sufficient such that third material 372 lines at least a portion of interior wall 100 that defines internal passage 82. For another example, third material 372 is a bond coat material, and a concentration of third material 372 proximate interior wall 100 is sufficient to facilitate bonding second material 362 to component material 78 and/or first material 322 proximate interior wall 100.

In the exemplary embodiment, inner core material 326 is a refractory ceramic material selected to withstand a high temperature environment associated with the molten state of component material 78 used to form component 80. For example, but without limitation, inner core material 326 includes at least one of silica, alumina, and mullite. Moreover, in the exemplary embodiment, inner core material 326 is selectively removable from component 80 to form internal passage 82. For example, but not by way of limitation, inner core material 326 is removable from component 80 by a suitable process that does not substantially degrade component material 78, such as, but not limited to, a suitable chemical leaching process. In certain embodiments, inner core material 326 is selected based on a compatibility with, and/or a removability from, component material 78, first material 322, and/or second material 362. In alternative embodiments, inner core material 326 is any suitable material that enables component 80 to be formed as described herein.

In some embodiments, jacketed core 310 is formed by filling hollow structure 320 with inner core material 326. For example, but not by way of limitation, inner core material 326 is injected as a slurry into hollow structure 320, and inner core material 326 is dried within hollow structure 320 to form jacketed core 310. Moreover, in certain embodiments, hollow structure 320 substantially structurally reinforces inner core 324, thus reducing potential problems that would be associated with production, handling, and use of an unreinforced inner core 324 to form component 80 in some embodiments. For example, in certain embodiments, inner core 324 is a relatively brittle ceramic material subject to a relatively high risk of fracture, cracking, and/or other damage. Thus, in some such embodiments, forming and transporting jacketed core 310 presents a much lower risk of damage to inner core 324, as compared to using an unjacketed inner core 324. Similarly, in some such embodiments, forming a suitable pattern around jacketed core 310 to be used for investment casting of mold 300, such as by injecting a wax pattern material into a pattern die around jacketed core 310, presents a much lower risk of damage to inner core 324, as compared to using an unjacketed inner core 324. Thus, in certain embodiments, use of jacketed core 310 presents a much lower risk of failure to produce an acceptable component 80 having internal passage 82 defined therein, as compared to the same steps if performed using an unjacketed inner core 324 rather than jacketed core 310. Thus, jacketed core 310 facilitates obtaining advantages associated with positioning inner core 324 with respect to mold 300 to define internal passage 82, while reducing or eliminating fragility problems associated with inner core 324. In alternative embodiments, hollow structure 320 does not substantially structurally reinforce inner core 324.

For example, in certain embodiments, such as, but not limited to, embodiments in which component **80** is rotor blade **70**, characteristic width **330** of inner core **324** is within a range from about 0.050 cm (0.020 inches) to about 1.016 cm (0.400 inches), and wall thickness **328** of hollow structure **320** is selected to be within a range from about 0.013 cm (0.005 inches) to about 0.254 cm (0.100 inches). More particularly, in some such embodiments, characteristic width **330** is within a range from about 0.102 cm (0.040 inches) to about 0.508 cm (0.200 inches), and wall thickness **328** is selected to be within a range from about 0.013 cm (0.005 inches) to about 0.038 cm (0.015 inches). For another example, in some embodiments, such as, but not limited to, embodiments in which component **80** is a stationary component, such as but not limited to stator vane **72**, characteristic width **330** of inner core **324** is greater than about 1.016 cm (0.400 inches), and/or wall thickness **328** is selected to be greater than about 0.254 cm (0.100 inches). In alternative embodiments, characteristic width **330** is any suitable value that enables the resulting internal passage **82** to perform its intended function, and wall thickness **328** is selected to be any suitable value that enables jacketed core **310** to function as described herein.

In certain embodiments, hollow structure **320** is formed using a suitable additive manufacturing process. For example, FIG. 7 is a schematic sectional view of an embodiment of hollow structure **320** formed from first material **322** and second material **362**. In the exemplary embodiment, hollow structure **320** extends from a first end **350** to an opposite second end **352**, and includes a radially inner layer of second material **362** and a radially outer layer of first material **322** that each extend from first end **350** to second end **352**, such that second material **362** defines interior portion **360** of hollow structure **320** and first material **322** defines outer wall **380** of hollow structure **320**.

To form hollow structure **320**, a computer design model of hollow structure **320** is sliced into a series of thin, parallel planes between first end **350** and second end **352**, such that a distribution of each of first material **322** and second material **362** within each plane is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material **322** and second material **362** from first end **350** to second end **352** in accordance with the model slices to form hollow structure **320**. For example, the additive manufacturing process is suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material **322** and second material **362** in each layer. Three such representative layers are indicated as layers **366**, **368**, and **370**. In some embodiments, the successive layers each including first material **322** and second material **362** are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material **322** and second material **362** are deposited using any suitable process that enables hollow structure **320** to be formed as described herein.

In some embodiments, the formation of hollow structure **320** by an additive manufacturing process enables hollow structure **320** to be formed with a distribution of second material **362** that would be difficult and/or relatively more costly to produce by other methods of forming hollow

structure **320**. Correspondingly, the formation of hollow structure **320** by an additive manufacturing process enables component **80** to be formed with an integral distribution of second material **362** proximate interior wall **100** (shown, for example, in FIG. 6) that would be difficult and/or relatively more costly to (i) produce by other methods of forming component **80**, and/or (ii) add to component **80** in a separate process after initial formation of component **80** in mold **300**.

For another example, FIG. 8 is a schematic sectional view of another embodiment of hollow structure **320** formed from first material **322** and second material **362**. In the exemplary embodiment, hollow structure **320** again includes a layer of first material **322** that extends from first end **350** to second end **352**. Hollow structure **320** also includes a layer of second material **362** that extends over at least one predefined first longitudinal portion **354** of interior portion **360** of hollow structure **320**, radially inward of first material **322**. In the exemplary embodiment, the at least one predefined first longitudinal portion **354** is a plurality of spaced apart first longitudinal portions **354**.

To form hollow structure **320**, a computer design model of hollow structure **320** is again sliced into a series of thin, parallel planes between first end **350** and second end **352**, such that a distribution of each of first material **322** and, for first longitudinal portions **354**, second material **362** within each plane is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material **322** and, for first longitudinal portions **354**, second material **362** from first end **350** to second end **352** in accordance with the model slices to form hollow structure **320**. For example, the additive manufacturing process is suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material **322** and, for first longitudinal portions **354**, second material **362** in each layer. Three such representative layers are indicated as layers **366**, **368**, and **370**. In some embodiments, the successive layers each including first material **322** and, for first longitudinal portions **354**, second material **362** are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material **322** and second material **362** are deposited using any suitable process that enables hollow structure **320** to be formed as described herein.

In some embodiments, the formation of hollow structure **320** by an additive manufacturing process again enables hollow structure **320** to be formed with a distribution of second material **362** that would be difficult and/or relatively more costly to produce by other methods of forming hollow structure **320**. Correspondingly, the formation of hollow structure **320** by an additive manufacturing process enables component **80** again to be formed with an integral distribution of second material **362** proximate interior wall **100** (shown in FIG. 6) that would be difficult and/or relatively more costly to (i) produce by other methods of forming component **80**, and/or (ii) add to component **80** in a separate process after initial formation of component **80** in mold **300**. In particular, the formation of hollow structure **320** by an additive manufacturing process enables component **80** to be formed with second material **362** distributed only at selected longitudinal locations along interior wall **100**. For example, in certain embodiments, second material **362** is relatively

expensive, and the formation of hollow structure 320 by an additive manufacturing process enables second material 362 to be located only at first longitudinal portions 354 of hollow structure 320 corresponding to locations along internal passage 82 where use of second material 362 is necessary to achieve a specified design criterion, thereby reducing a cost associated with distributing second material 362 along an entire length of internal passage 82.

For another example, FIG. 9 is a schematic sectional view of another embodiment of hollow structure 320 formed from first material 322, second material 362, and third material 372. In the exemplary embodiment, hollow structure 320 again includes a layer of first material 322 that extends from first end 350 to second end 352. Hollow structure 320 also includes a layer of second material 362 that extends over at least one predefined first longitudinal portion 354 of interior portion 360 of hollow structure 320 radially inward of first material 322, and a layer of third material 372 that extends over at least one predefined second longitudinal portion 356 of interior portion 360 of hollow structure 320 radially inward of first material 322. In the exemplary embodiment, the at least one predefined first longitudinal portion 354 is a plurality of first longitudinal portions 354, and the at least one predefined second longitudinal portion 356 is a plurality of second longitudinal portions 356 that alternate with the plurality of first longitudinal portions 354 along interior portion 360.

To form hollow structure 320, a computer design model of hollow structure 320 is again sliced into a series of thin, parallel planes between first end 350 and second end 352, such that a distribution within each plane of each of first material 322, second material 362 for first longitudinal portions 354, and third material 372 for second longitudinal portions 356, is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material 322, second material 362, and/or third material 372 from first end 350 to second end 352 in accordance with the model slices to form hollow structure 320. For example, the additive manufacturing process is suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material 322 and, for first longitudinal portions 354, second material 362, and, for second longitudinal portions 356, third material 372 in each layer. Three such representative layers are indicated as layers 366, 368, and 370. In some embodiments, the successive layers each including first material 322 and, for first longitudinal portions 354, second material 362, and, for second longitudinal portions 356, third material 372 are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material 322, second material 362, and/or third material 372 are deposited using any suitable process that enables hollow structure 320 to be formed as described herein.

In some embodiments, the formation of hollow structure 320 by an additive manufacturing process enables hollow structure 320 to be formed with a distribution of second material 362 and third material 372 that would be difficult and/or relatively more costly to produce by other methods of forming hollow structure 320. Correspondingly, the formation of hollow structure 320 by an additive manufacturing

process enables component 80 to be formed with an integral distribution of second material 362 proximate selected portions of interior wall 100 (shown in FIG. 6), and a similar integral distribution of third material 372 proximate other selected portions of interior wall 100, that would be difficult and/or relatively more costly to (i) produce by other methods of forming component 80, and/or (ii) add to component 80 in a separate process after initial formation of component 80 in mold 300. In particular, the formation of hollow structure 320 by an additive manufacturing process enables component 80 to be formed with each of second material 362 and third material 372 distributed only at selected respective longitudinal locations along interior wall 100. For example, in certain embodiments, second material 362 provides a thermal barrier of a first effectiveness and third material 372 provides a thermal barrier of a second, greater effectiveness and is correspondingly more expensive, and the formation of hollow structure 320 by an additive manufacturing process enables third material 372 to be located only at second longitudinal portions 356 of hollow structure 320 corresponding to locations along internal passage 82 where use of third material 372 is necessary to achieve a specified design thermal criterion, thereby reducing a cost associated with distributing third material 372 along an entire length of internal passage 82.

For another example, FIG. 10 is a schematic sectional view of another embodiment of hollow structure 320 formed from first material 322, second material 362, and third material 372. The exemplary embodiment is substantially similar to the embodiment shown in FIG. 9, except that at least one of plurality of second longitudinal portions 356 and plurality of first longitudinal portions 354 is spaced apart along interior portion 360 from others of plurality of second longitudinal portions 356 and plurality of first longitudinal portions 354.

To form hollow structure 320, a computer design model of hollow structure 320 is again sliced into a series of thin, parallel planes between first end 350 and second end 352, such that a distribution within each plane of each of first material 322, second material 362 for first longitudinal portions 354, and third material 372 for second longitudinal portions 356, is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material 322, second material 362, and/or third material 372 from first end 350 to second end 352 in accordance with the model slices to form hollow structure 320. For example, the additive manufacturing process is suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material 322 and, for first longitudinal portions 354, second material 362, and, for second longitudinal portions 356, third material 372 in each layer. Three such representative layers are indicated as layers 366, 368, and 370. In some embodiments, the successive layers each including first material 322 and, for first longitudinal portions 354, second material 362, and, for second longitudinal portions 356, third material 372 are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material 322, second material 362,

and/or third material 372 are deposited using any suitable process that enables hollow structure 320 to be formed as described herein.

In some embodiments, the formation of hollow structure 320 by an additive manufacturing process again enables hollow structure 320 to be formed with a distribution of second material 362 and third material 372 that would be difficult and/or relatively more costly to produce by other methods of forming hollow structure 320. Correspondingly, the formation of hollow structure 320 by an additive manufacturing process enables component 80 to be formed with an integral distribution of second material 362 proximate selected portions of interior wall 100 (shown in FIG. 6), and a similar integral distribution of third material 372 proximate other selected portions of interior wall 100, that would be difficult and/or relatively more costly to (i) produce by other methods of forming component 80, and/or (ii) add to component 80 in a separate process after initial formation of component 80 in mold 300. In particular, the formation of hollow structure 320 by an additive manufacturing process enables component 80 to be formed with each of second material 362 and third material 372 distributed only at selected respective longitudinal locations along interior wall 100. For example, in certain embodiments, second material 362 provides a thermal barrier of a first effectiveness and is more expensive than first material 322, and third material 372 provides a thermal barrier of a second, greater effectiveness and is more expensive than second material 362. The formation of hollow structure 320 by an additive manufacturing process enables second material 362 to be located only at first longitudinal portions 354 of hollow structure 320 corresponding to locations along internal passage 82 where use of second material 362 is necessary to achieve a first specified design thermal criterion, and third material 372 to be located only at second longitudinal portions 356 of hollow structure 320 corresponding to locations along internal passage 82 where use of third material 372 is necessary to achieve a second, more stringent specified design thermal criterion, thereby reducing a cost associated with distributing at least one of second material 362 and third material 372 along an entire length of internal passage 82.

FIG. 11 is a schematic sectional view of a portion of another exemplary component 80 that includes internal passage 82 having a plurality of interior passage features 98. FIG. 12 is a schematic perspective cutaway view of another exemplary jacketed core 310 for use in mold assembly 301 to form component 80 having interior passage features 98 as shown in FIG. 11. In particular, a portion of hollow structure 320 is cut away in the view of FIG. 12 to illustrate features of inner core 324. FIG. 13 is a schematic sectional view of a portion of another hollow structure 320 for use in forming jacketed core 310. Hollow structure 320 again is formed from first material 322 and second material 362.

With reference to FIGS. 11-13, internal passage 82 again is generally defined by interior wall 100 of component 80, and interior passage features 98 are shaped to define local variations in a flow path defined by internal passage 82. For example, but not by way of limitation, interior passage features 98 are turbulators that extend radially inward from interior wall 100 generally towards a center of internal passage 82, and are shaped to disrupt a thermal boundary layer flow along interior wall 100 to improve a heat transfer capability of a cooling fluid provided to internal passage 82 during operation of rotary machine 10 (shown in FIG. 1). Alternatively, interior passage features 98 are any structure shaped to define local variations in the flow path defined by

internal passage 82. In the exemplary embodiment, component 80 proximate each interior passage feature 98 is at least partially formed by second material 362, as will be described herein. A distribution of first material 322 within component 80 is omitted from FIG. 11 for clarity.

In certain embodiments, interior portion 360 of hollow structure 320 is shaped to define the at least one interior passage feature 98. In some such embodiments, inner core 324 is complementarily shaped by interior portion 360 of hollow structure 320 such that inner core 324 defines internal passage 82 including at least one interior passage feature 98 defined therein. For example, inner core 324 is complementarily shaped by interior portion 360 to include at least one complementary feature 331, and the at least one complementary feature 331 has a shape complementary to a shape of at least one interior passage feature 98.

For example, in the illustrated embodiment, the at least one complementary feature 331 is a plurality of recessed features 334 defined in an exterior surface of inner core 324. Each recessed feature 334 has a shape complementary to a shape of a corresponding interior passage feature 98. More specifically, in the illustrated embodiment, interior portion 360 of hollow structure 320 includes protrusions 341 formed as a plurality of stud shapes that extend radially inwardly on interior portion 360 of hollow structure 320, such that when inner core material 326 is added to hollow structure 320, protrusions 341 define recessed features 334. Thus, when molten component material 78 is introduced into mold cavity 304 and hollow structure 320 is at least partially absorbed into molten component material 78, molten component material 78 fills in against the at least one complementary feature 331, and cooled component material 78 within the at least one complementary feature 331 forms the at least one interior passage feature 98. Additionally or alternatively, to an extent that a portion of interior portion 360 of hollow structure 320 adjacent inner core 324 remains intact after molten component material 78 is introduced into mold cavity 304 and cooled, the intact portion of interior portion 360 coupled against the at least one complementary feature 331 defines the at least one interior passage feature 98.

In the exemplary embodiment, interior portion 360 of hollow structure 320 includes at least protrusions 341 formed at least partially from second material 362, and a remainder of hollow structure 320 formed from first material 322. In alternative embodiments, hollow structure 320 includes any suitable distribution of first material 322 and second material 362. In some embodiments, after jacketed core 310 is positioned with respect to mold 300 (shown in FIG. 3) and molten component material 78 is added to mold cavity 304 and cooled to form component 80, a concentration of second material 362 proximate interior passage features 98 is detectably higher than a concentration of second material 362 at other locations within component 80. Moreover, in some such embodiments, second material 362 forms at least a portion of interior passage features 98.

To form hollow structure 320, a computer design model of hollow structure 320 again is sliced into a series of thin, parallel planes between first end 350 and second end 352, such that a distribution of each of first material 322 and second material 362 within each plane is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material 322 and, for layers in which at least one protrusion 341 is partially defined, second material 362 from first end 350 to second end 352 in accordance with the model slices to form hollow structure 320. For example, the additive manufacturing process is

again suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material **322** and second material **362** in each layer. One such representative layer is indicated as layer **366**. In some embodiments, the successive layers each including first material **322** and, for layers in which at least one protrusion **341** is partially defined, second material **362** are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material **322** and second material **362** are deposited using any suitable process that enables hollow structure **320** to be formed as described herein.

In some embodiments, the formation of hollow structure **320** by an additive manufacturing process enables hollow structure **320** to be formed with protrusions **341** formed at least partially from second material **362** that would be difficult and/or relatively more costly to produce by other methods of forming hollow structure **320**. Correspondingly, the formation of hollow structure **320** by an additive manufacturing process enables component **80** to be formed with interior passage features **98** formed at least partially from second material **362** that would be difficult and/or relatively more costly to (i) produce by other methods of forming component **80**, and/or (ii) add to component **80** in a separate process after initial formation of component **80** in mold **300**. For example, in certain embodiments, second material **362** is relatively more resistant to corrosion than first material **322**, but also relatively more expensive, such that use of second material **362** is selected for use to facilitate preserving a shape of interior passage features **98** against corrosion and first material **322** and/or component material **78** are sufficient to achieve a specified anti-corrosion design criterion for other portions of interior wall **100**, thereby reducing a cost associated with component **80**.

FIG. **14** is a schematic sectional view of a portion of another exemplary component **80** that includes internal passage **82** having a plurality of interior passage features **98**. FIG. **15** is a schematic perspective cutaway view of another exemplary jacketed core **310** for use in mold assembly **301** to form component **80** having interior passage features **98** as shown in FIG. **14**. In particular, a portion of hollow structure **320** is cut away in the view of FIG. **15** to illustrate features of inner core **324**. FIG. **16** is a schematic sectional view of a portion of another hollow structure **320** for use in forming jacketed core **310**. Hollow structure **320** again is formed from first material **322** and second material **362**.

With reference to FIGS. **14-16**, internal passage **82** again is generally defined by interior wall **100** of component **80**, and interior passage features **98** again are shaped to define local variations in a flow path defined by interior passage **82**. In the exemplary embodiment, component **80** proximate each interior passage feature **98** again is at least partially formed by second material **362**, as will be described herein. A distribution of first material **322** within component **80** is omitted from FIG. **14** for clarity.

In certain embodiments, interior portion **360** of hollow structure **320** again is shaped to define the at least one interior passage feature **98**. In some such embodiments, inner core **324** again is complementarily shaped by interior portion **360** of hollow structure **320** such that inner core **324** defines internal passage **82** including at least one interior

passage feature **98** defined therein. More specifically, in the exemplary embodiment, interior portion **360** of hollow structure **320** is shaped to define the at least one interior passage feature **98** as a rifled groove along interior wall **100** of internal passage **82**. Correspondingly, interior portion **360** includes a rifled protrusion **341** shaped to define the at least one complementary feature **331** of inner core **324** as a rifled groove structure **339** when inner core material **326** is added to hollow structure **320**. Thus, when molten component material **78** is introduced into mold cavity **304** and hollow structure **320** is at least partially absorbed into molten component material **78**, molten component material **78** fills in against the at least one complementary feature **331**, and cooled component material **78** within the at least one complementary feature **331** again forms the at least one interior passage feature **98**. Additionally or alternatively, to an extent that a portion of interior portion **360** of hollow structure **320** adjacent inner core **324** remains intact after molten component material **78** is introduced into mold cavity **304** and cooled, the intact portion of interior portion **360** coupled against the at least one complementary feature **331** again defines the at least one interior passage feature **98**.

In the exemplary embodiment, hollow structure **320** includes at least protrusions **341** formed at least partially from second material **362**, and a remainder of hollow structure **320** formed from first material **322**. In alternative embodiments, hollow structure **320** includes any suitable distribution of first material **322** and second material **362**. In some embodiments, after jacketed core **310** is positioned with respect to mold **300** (shown in FIG. **3**) and molten component material **78** is added to mold cavity **304** and cooled to form component **80**, a concentration of second material **362** proximate interior passage features **98** is detectably higher than a concentration of second material **362** at other locations within component **80**. Moreover, in some such embodiments, second material **362** forms at least a portion of interior passage features **98**.

To form hollow structure **320**, a computer design model of hollow structure **320** again is sliced into a series of thin, parallel planes between first end **350** and second end **352**, such that a distribution of each of first material **322** and second material **362** within each plane is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material **322** and, for layers in which protrusion **341** is partially defined, second material **362** from first end **350** to second end **352** in accordance with the model slices to form hollow structure **320**. For example, the additive manufacturing process is again suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material **322** and second material **362** in each layer. One such representative layer is indicated as layer **366**. In some embodiments, the successive layers each including first material **322** and, for layers in which protrusion **341** is partially defined, second material **362** are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material **322** and second material **362** are deposited using any suitable process that enables hollow structure **320** to be formed as described herein.

In some embodiments, the formation of hollow structure 320 by an additive manufacturing process again enables component 80 to be formed with interior passage features 98 formed at least partially from second material 362 that would be difficult and/or relatively more costly to (i) produce by other methods of forming component 80, and/or (ii) add to component 80 in a separate process after initial formation of component 80 in mold 300, as described above.

With reference to FIGS. 11-16, although interior passage features 98 are illustrated studs and/or rifled grooves, it should be understood that this disclosure contemplates interior passage features 98 having any suitable additional or alternative shape that enables internal passage 82 to function for its intended purpose, and interior portion 360 of hollow structure 320 and complementary features 331 of inner core 324 having any suitable corresponding shape that enables interior passage features 98 to be formed as described herein. Moreover, although the illustrated embodiments show each embodiment of interior passage features 98 as having a substantially identical repeating shape, it should be understood that this disclosure contemplates interior passage features 98 having any suitable combination of different shapes that enables internal passage 82 to function for its intended purpose, and interior portion 360 of hollow structure 320 and complementary features 331 of inner core 324 having any suitable corresponding combination of different shapes that enables interior passage features 98 to be formed as described herein.

FIG. 17 is a schematic sectional view of a portion of another exemplary component 80 that includes internal passage 82 defined therein. FIG. 18 is a schematic sectional view of a portion of another hollow structure 320 for use in mold assembly 301 to form component 80 shown in FIG. 17. Hollow structure 320 again is formed from first material 322 and second material 362. In the exemplary embodiment, second material 362 is a relatively higher strength material than first material 322. Alternatively, second material 362 is a material capable of joining synergistically with at least one of component material 78 and first material 322 to improve upon a structural strength characteristic of the at least one of component material 78 and first material 322.

With reference to FIGS. 17 and 18, internal passage 82 again is defined by interior wall 100 of component 80. In the exemplary embodiment, a shape of internal passage 82 defines at least one stress concentration region 102 in component 80 proximate interior wall 100. A concentration of second material 362 proximate the at least one stress concentration region 102 facilitates an increased stress resistance of component 80 in the at least one stress concentration region 102. A distribution of first material 322 within component 80 is omitted from FIG. 17 for clarity.

In certain embodiments, inner core 324 (not shown) again is complementarily shaped by interior portion 360 of hollow structure 320 such that inner core 324 defines internal passage 82 including the at least one stress concentration region 102. At least one portion 358 of hollow structure 320 corresponding to the at least one stress concentration region 102 is at least partially formed from second material 362, and a remainder of hollow structure 320 is formed from first material 322. In alternative embodiments, hollow structure 320 includes any suitable distribution of first material 322 and second material 362. Hollow structure 320 is then filled with inner core material 326 to form jacketed core 310 similar to that shown in FIG. 3. In some embodiments, after jacketed core 310 is positioned with respect to mold 300 (shown in FIG. 3) and molten component material 78 is added to mold cavity 304 and cooled to form component 80,

second material 362 forms at least a portion of the at least one stress concentration region 102.

To form hollow structure 320, a computer design model of hollow structure 320 again is sliced into a series of thin, parallel planes between first end 350 and second end 352, such that a distribution of each of first material 322 and second material 362 within each plane is defined. A computer numerically controlled (CNC) machine deposits successive layers of first material 322 and/or second material 362 from first end 350 to second end 352 in accordance with the model slices to form hollow structure 320. For example, the additive manufacturing process is again suitably configured for alternating deposition of each of a plurality of metallic and/or metallic and ceramic materials, and the alternating deposition is suitably controlled according to the computer design model to produce the defined distribution of first material 322 and second material 362 in each layer. Three such representative layers are indicated as layers 366, 368, and 370. In some embodiments, the successive layers each including first material 322 and/or second material 362 are deposited using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process. Additionally or alternatively, the successive layers of first material 322 and second material 362 are deposited using any suitable process that enables hollow structure 320 to be formed as described herein.

In some embodiments, the formation of hollow structure 320 by an additive manufacturing process again enables hollow structure 320 to be formed with a distribution of second material 362 that would be difficult and/or relatively more costly to produce by other methods of forming hollow structure 320. Correspondingly, the formation of hollow structure 320 by an additive manufacturing process enables component 80 to be formed with an integral distribution of second material 362 proximate the at least one stress concentration region 102 that would be difficult and/or relatively more costly to (i) produce by other methods of forming component 80, and/or (ii) add to component 80 in a separate process after initial formation of component 80 in mold 300.

With further reference to FIGS. 7-18, although the illustrated embodiments show internal passage 82 as having a generally circular cross-section, it should be understood that internal passage 82 has any suitable additional or alternative cross-section that enables internal passage 82 to function for its intended purpose. Moreover, although the illustrated embodiments show each embodiment of internal passage 82 as having a generally constant cross-section along its length, it should be understood that internal passage 82 has any suitable variation in cross-section along its length that enables internal passage 82 to function for its intended purpose. Further, it should be understood that hollow structure 320 is shaped to define any suitable corresponding shape of internal passage 82 in any suitable fashion that enables hollow structure 320 to be formed as described herein.

An exemplary method 1900 of forming a component, such as component 80, having an internal passage defined therein, such as internal passage 82, is illustrated in a flow diagram in FIGS. 19 and 20. With reference also to FIGS. 1-18, exemplary method 1900 includes positioning 1902 a jacketed core, such as jacketed core 310, with respect to a mold, such as mold 300. The jacketed core includes a hollow structure, such as hollow structure 320, formed from at least

a first material, such as first material **322**, and a second material, such as second material **362**. The jacketed core also includes an inner core, such as inner core **324**, disposed within the hollow structure. Method **1900** also includes introducing **1904** a component material, such as component material **78**, in a molten state into a cavity of the mold, such as mold cavity **304**, to form the component, and cooling **1906** the component material in the cavity to form the component. The inner core defines the internal passage within the component.

In some embodiments, the step of introducing **1904** the component material into the cavity includes introducing **1908** the component material such that, after the component is formed, a concentration of the second material proximate the inner core is sufficient to establish at least one material characteristic associated with the second material along at least a portion of an interior wall, such as interior wall **100**, that defines the internal passage within the component.

In certain embodiments, the step of introducing **1904** the component material into the cavity includes introducing **1910** the component material such that, after the component is formed, the second material lines at least a portion of an interior wall, such as interior wall **100**, that defines the internal passage within the component.

In some embodiments, the step of positioning **1902** the jacketed core includes positioning **1912** the jacketed core wherein the second material is selected from at least one of (i) an oxidation-inhibiting material, (ii) a corrosion-inhibiting material, (iii) a carbon-deposition-inhibiting material, (iv) a thermal barrier material, (v) a water vapor barrier material, and (vi) a wear-inhibiting material, and (vii) a material that increases a structural strength of the component along the internal passageway when the component is formed.

In certain embodiments, the step of positioning **1902** the jacketed core includes positioning **1914** the jacketed core wherein the second material extends over at least one predefined first longitudinal portion, such as first longitudinal portion **354**, of an interior portion of the hollow structure, such as interior portion **360**, radially inward of the first material. In some such embodiments, the step of positioning **1914** the jacketed core includes positioning **1916** the jacketed core that includes the hollow structure formed from the first material, the second material, and a third material, such as third material **372**. The third material extends over at least one predefined second longitudinal portion of the interior portion of the hollow structure, such as second longitudinal portion **356**, radially inward of the first material.

In certain embodiments, an interior portion of the hollow structure, such as interior portion **360**, is at least partially formed from the second material, the interior portion is shaped to define at least one interior passage feature of the internal passage, such as interior passage feature **98**, and the step of introducing **1904** the component material into the cavity includes introducing **1918** the component material such that, after the component is formed, the second material forms at least a portion of the at least one interior passage feature.

In some embodiments, a shape of the internal passage defines at least one stress concentration region in the component, such as stress concentration region **102**. Additionally, at least one portion of the hollow structure, such as portion **358**, corresponding to the at least one stress concentration region is at least partially formed from the second material. The step of introducing **1904** the component material into the cavity includes introducing **1920** the component

material such that, after the component is formed, the second material forms at least a portion of the at least one stress concentration region.

In certain embodiments, the step of positioning **1902** the jacketed core includes positioning **1922** the jacketed core that includes the hollow structure that includes a plurality of layers, such as representative layers **366**, **368**, and **370**, each formed using an additive manufacturing process.

In some embodiments, method **1900** further includes forming **1924** the hollow structure using **1926** an additive manufacturing process. Moreover, in some such embodiments, the step of using **1926** an additive manufacturing process includes alternately depositing **1928** each of the first material and the second material to produce a defined distribution of the first material and the second material in each of a plurality of layers of the hollow structure, such as representative layers **366**, **368**, and **370**. Additionally or alternatively, in some such embodiments, the step of using **1926** an additive manufacturing process includes using **1930** at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process.

The above-described jacketed core provides a cost-effective method for forming components that include internal passages defined therein with materials other than the component material selectively positioned along the internal passage. Specifically, the jacketed core includes the inner core, which is positioned within the mold cavity to define the position of the internal passage within the component, and also includes the hollow structure, within which the inner core is disposed, formed from at least a first material and a second material. The second material is strategically distributed within the hollow structure, such as by an additive manufacturing process, such that the second material is selectively positioned along the internal passage when the component is formed in the mold. For example, but not by way of limitation, the second material is selectively positioned to provide an anti-corrosion coating for turbulators disposed along the internal passage, or to structurally reinforce a stress concentration associated with a shape of the internal passage. As just one illustration, a relatively lower strength component material meets strength requirements for most portions of the component and is selected to provide a better overall thermal performance for the component, and the selective addition of the second material near the internal passage enables greater localized strength as needed in an area where thermal performance is relatively less critical.

Also, specifically, the first material and the second material are each at least partially absorbable by the molten component material introduced into the mold cavity to form the component. Thus, the use of the hollow structure does not interfere with the structural or performance characteristics of the component, and does not interfere with the later removal of the inner core material from the component to form the internal passage.

An exemplary technical effect of the methods, systems, and apparatus described herein includes at least one of: (a) reducing or eliminating fragility problems associated with forming, handling, transport, and/or storage of the core used in forming a component having an internal passage defined therein; and (b) an ability to reliably and repeatably selectively position a second material along the internal passage when the component is formed in the mold, even for internal

passages having nonlinear and/or complex shapes and/or characterized by high L/d ratios.

Exemplary embodiments of jacketed cores are described above in detail. The jacketed cores, and methods and systems using such jacketed cores, are not limited to the specific embodiments described herein, but rather, components of systems and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. For example, the exemplary embodiments can be implemented and utilized in connection with many other applications that are currently configured to use cores within mold assemblies.

Although specific features of various embodiments of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to disclose the embodiments, including the best mode, and also to enable any person skilled in the art to practice the embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A method of forming a component having an internal passage defined therein, said method comprising:

positioning a jacketed core with respect to a mold, wherein the jacketed core includes:

a hollow structure consisting of a plurality of metallic materials including at least a first material and a second material; and

an inner core disposed within the hollow structure;

introducing a component material in a molten state into a cavity of the mold; and

cooling the component material in the cavity to form the component, wherein the inner core defines the internal passage within the component.

2. The method of claim 1, wherein said introducing the component material into the cavity comprises introducing the component material such that, after the component is formed, a concentration of the second material proximate the inner core is sufficient to establish at least one material characteristic associated with the second material along at least a portion of an interior wall that defines the internal passage within the component.

3. The method of claim 1, wherein said introducing the component material into the cavity comprises introducing the component material such that, after the component is formed, the second material lines at least a portion of an interior wall that defines the internal passage within the component.

4. The method of claim 1, wherein said positioning the jacketed core comprises positioning the jacketed core wherein the second material is selected from at least one of (i) an oxidation-inhibiting material, (ii) a corrosion-inhibiting material, (iii) a carbon-deposition-inhibiting material, (iv) a thermal barrier material, (v) a water vapor barrier material, and (vi) a wear-inhibiting material, and (vii) a

material that increases a structural strength of the component along the internal passageway when the component is formed.

5. The method of claim 1, wherein said positioning the jacketed core comprises positioning the jacketed core wherein the second material extends over at least one predefined first longitudinal portion of an interior portion of the hollow structure, radially inward of the first material.

6. The method of claim 5, wherein said positioning the jacketed core comprises positioning the jacketed core that includes the hollow structure formed from the first material, the second material, and a third material, and wherein the third material extends over at least one predefined second longitudinal portion of the interior portion of the hollow structure, radially inward of the first material.

7. The method of claim 1, wherein an interior portion of the hollow structure is at least partially formed from the second material, the interior portion shaped to define at least one interior passage feature of the internal passage, said introducing the component material into the cavity comprises introducing the component material such that, after the component is formed, the second material forms at least a portion of the at least one interior passage feature.

8. The method of claim 1, wherein a shape of the internal passage defines at least one stress concentration region in the component, and wherein at least one portion of the hollow structure corresponding to the at least one stress concentration region is at least partially formed from the second material, said introducing the component material into the cavity comprises introducing the component material such that, after the component is formed, the second material forms at least a portion of the at least one stress concentration region.

9. The method of claim 1, wherein said positioning the jacketed core comprises positioning the jacketed core that includes the hollow structure that includes a plurality of layers each formed using an additive manufacturing process.

10. The method of claim 1, further comprising forming the hollow structure using an additive manufacturing process.

11. The method of claim 10, wherein using an additive manufacturing process comprises alternately depositing each of the first material and the second material to produce a defined distribution of the first material and the second material in each of a plurality of layers of the hollow structure.

12. The method of claim 10, wherein using an additive manufacturing process comprises using at least one of a direct metal laser melting (DMLM) process, a direct metal laser sintering (DMLS) process, a selective laser sintering (SLS) process, an electron beam melting (EBM) process, a selective laser melting process (SLM), and a robocasting extrusion-type additive process.

13. A mold assembly for use in forming a component having an internal passage defined therein, said mold assembly comprising:

a mold defining a mold cavity therein; and

a jacketed core positioned with respect to said mold, said jacketed core comprising:

a hollow structure consisting of a plurality of metallic materials including at least a first material and a second material; and

an inner core disposed within said hollow structure, wherein said inner core is positioned to define the internal passage within the component when a component material in a molten state is introduced into said mold cavity and cooled to form the component.

25

14. The mold assembly of claim 13, wherein said second material is selected from at least one of (i) an oxidation inhibiting material, (ii) a corrosion-inhibiting material, (iii) a carbon-deposition-inhibiting material, (iv) a thermal barrier material, (v) a water vapor barrier material, and (vi) a wear-inhibiting material, and (vii) a material that increases a structural strength of the component along the internal passageway when the component is formed.

15. The mold assembly of claim 13, wherein said second material extends over at least one predefined first longitudinal portion of an interior portion of said hollow structure, radially inward of said first material.

16. The mold assembly of claim 13, wherein said hollow structure is formed from said first material, said second material, and a third material, said third material extends over at least one predefined second longitudinal portion of said interior portion of said hollow structure, radially inward of said first material.

17. The mold assembly of claim 13, wherein said hollow structure comprises an interior portion at least partially formed from said second material, said interior portion shaped to define at least one interior passage feature of the internal passage when the component is formed.

18. The mold assembly of claim 13, wherein a shape of the internal passage defines at least one stress concentration region in the component, and wherein at least one portion of said hollow structure corresponding to the at least one stress concentration region is at least partially formed from said second material.

19. The mold assembly of claim 13, wherein said second material is at least one of:

26

a relatively higher strength material than said first material, and capable of joining synergistically with at least one of the component material and said first material such that a structural strength characteristic of said at least one of the component material and said first material is improved.

20. The mold assembly of claim 13, wherein said hollow structure comprises a plurality of layers each formed using an additive manufacturing process.

21. A mold assembly for use in forming a component having an internal passage defined therein, said mold assembly comprising:

a mold defining a mold cavity therein; and
a jacketed core positioned with respect to said mold, said jacketed core comprising:

a hollow structure comprising an outer wall, an interior portion radially inward of said outer wall, and a plurality of protrusions that extend radially inwardly from said interior portion, wherein said outer wall is formed from a first material that is metallic, and wherein said plurality of protrusions is formed at least partially from a second material; and

an inner core disposed within said hollow structure, wherein said inner core comprises complementary features that receive said plurality of protrusions and is positioned to define the internal passage within the component when a component material in a molten state is introduced into said mold cavity and cooled to form the component.

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